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THE INFLUENCE OF WATER-DISPLACING ORGANIC CORROSION INHIBITORS --ETC(U)
JAN 82 A S MACHIN, J Y MANN
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MELBOURNE, VICTORIA

STRUCTURES REPORT 390

THE INFLUENCE OF WATER-DISPLACING ORGANIC CORROSION INHIBITORS ON THE FATIGUE BEHAVIOUR OF 2024-T3 ALCLAD ALUMINIUM ALLOY BOLTED JOINTS

by

A. S. MACHIN and J. Y. MANN

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THE INFLUENCE OF WATER-DISPLACING ORGANIC CORROSION INHIBITORS ON THE FATIGUE BEHAVIOUR OF 2024-T3 ALCLAD ALUMINIUM ALLOY BOLTED JOINTS

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SUMMARY

Some aircraft manufacturers and operators have attempted to control in-service corrosion by the use of water-displacing organic inhibitors which can be either brushed or sprayed onto corrosion-susceptible areas of the structure. However, because of the low surface tension and lubricating properties of these preparations, concern has been expressed as to their potential side-effects on the fatigue performance of bolted and riveted joints.

Fatigue tests were carried out in repeated tension under both constant-amplitude and multi-load-level sequences on several types of 8-bolt double-lap joint specimens of 2024-T3 alclad aluminium alloy sheet. These included both low and high (100%) load transfer joints, using high and low bolt clamping forces in each case. Complementary tests were made on each type of joint assembled with either "dry" components or components coated with the corrosion inhibitor preparations LPS-3 or PX-112.

Contrary to the findings of previous investigations into the effect of inhibitors on riveted joints, the two corrosion inhibitors used were found, in general, to have either no effect or a beneficial effect on the fatigue lives of bolted joints. It is concluded that the specific effects of a water-displacing organic corrosion inhibitor on fatigue strength of joints are likely to be dependent on the type of joint, its configuration and on the severity of the load spectrum involved.

[*This Report is a revised version of a paper presented at the 10th ICAF Symposium held at Brussels 16–18 May 1979*].

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1. INTRODUCTION

Water-displacing organic corrosion-inhibiting preparations are being used by both aircraft manufacturers and operators in an attempt to reduce and control in-service corrosion. These preparations are usually a complex combination of high molecular weight hydrocarbons dissolved in a low surface tension volatile solvent containing a corrosion inhibitor. The solvent displaces moisture on the surface and promotes penetration of the liquid between the faying surfaces and into cracks by capillary action. Evaporation of the solvent releases a thin soft protective film composed of the hydrocarbons which because of their highly polar nature, tend to become attached to metal surfaces and further promote the displacement of moisture. A number of proprietary formulations are available including LPS-3 (Ref. 1), PX-112 (Ref. 2) and Boeshield T-9 (Ref. 3). Some of these water-displacing compounds are qualified to military specifications (Refs 4, 5) and commercial specifications (Ref. 6). Their general properties have been discussed by Lewis (Refs 7, 8).

Irrespective of their effectiveness in inhibiting or controlling corrosion in aircraft structures under service conditions, concern has been expressed as to the effect of polar organic corrosion inhibitors on the fatigue performance of bolted and riveted friction joints because of the potential lubricating properties of the hydrocarbon residue between the faying surfaces. Such a residue could change the load transfer characteristics of the joint by reducing that proportion of the force carried by friction between the joint surfaces and increasing the proportion carried in bearing through the bolts or rivets (Ref. 9).

Rotating bending fatigue tests (Refs 10, 11) on several steels have shown that by coating the specimens with polar non-corrosive organic lubricating compounds the lives are increased compared with those for uncoated specimens, while other work (Ref. 12) has indicated that the fatigue lives of specimens coated with polar substances are less than those when non-polar substances are used. Fatigue tests on single-lap riveted joints (Refs 13, 14) have shown that corrosion-inhibiting fluids can significantly reduce fatigue lives at high and medium alternating stresses. However, Schijve *et al.* (Ref. 15) after fatigue tests on a variety of symmetric and asymmetric riveted lap joints concluded that the effect of the corrosion-inhibiting preparation LPS-3 on fatigue life depends on the structural configuration of the joint, and that if load transfer by friction is relied upon the penetrant could adversely effect the life. Kiddle (Ref. 16), from tests on bolted joints, has concluded that the particular interfay sealant system which he used reduced fatigue lives at high stresses but increased them at low stresses. This suggests that the effects of corrosion inhibiting fluids on fatigue lives could be stress-level dependent.

This paper reports the results of a comprehensive investigation involving constant-amplitude and multi-load-level fatigue tests on 2024-T3 alclad aluminium alloy bolted joints representing both 'low' and 'high' load transfer construction and high and low bolt clamping forces, complementary tests being made in all cases with the joint components assembled either 'dry' or after coating with an organic corrosion-inhibiting preparation.

2. MATERIAL AND SPECIMENS

2.1 Test Material

Three sheets of 3·6 mm (0·140 inch) thick Alclad 2024-T3 aluminium alloy produced by Kaiser Aluminium (USA) from one cast to Specification QQ-A-250/5 were used for this investigation. The sheet size was 1220 mm × 3660 mm (48 × 144 inches). Table 1 indicates the static tensile properties of this test material, which was given the laboratory code FC.

TABLE 1

Static Tensile Properties of Material

Property		Average*	Proof / UTS	Specification QQ-A-250/5F (minimum)
0·1% Proof Stress (MPa)	L	360 s = 4 v = 0·011	0·75	—
	T	297 s = 2 v = 0·007	0·63	—
0·2% Proof Stress (MPa)	L	362 s = 4 v = 0·010	0·76	—
	T	315 s = 2 v = 0·007	0·67	276
Ultimate Tensile Stress (MPa)	L	478 s = 5 v = 0·010	—	—
	T	470 s = 1 v = 0·002	—	428
Elongation (%)	L	17·6 s = 0·9 v = 0·053	—	—
	T	19·1 s = 0·3 v = 0·033	—	15

L — Parallel to direction of final rolling; T — Perpendicular to direction of final rolling.
s — standard deviation; v — coefficient of variation.
* average of 12 L tests, 3 T tests.

2.2 Types of Specimens

The types of bolted joint fatigue specimens used in this investigation are detailed in Figure 1, while complete details of specimen manufacture and assembly are given in Appendix 1.

Each specimen was of a symmetrical double-lap configuration incorporating eight 0·375 inch diameter high tensile cadmium plated aircraft bolts, lock nuts with nylon inserts and cadmium plated steel washers under the nuts and the bolt heads. Two basically different types of specimens were used, a 'high-load transfer' (100%), specimen assembled from four sheet components (referred to as 4-piece), and a 'low-load transfer' specimen assembled from three components (referred to as 3-piece). All components were taken parallel to the final rolling direction of the sheets.

Components were assembled with the eight bolts either (a) fully torqued to the recommended value of 27 Nm (240 pound inches) including approximately 6 Nm (50 pound inches) to form the thread in the nylon inserts—these being designated 'tight' joints—or (b) tightened to barely exert any clamping force ('loose' joints). About half of the specimens of each joint type were assembled using components previously coated with either LPS-3 or PX-112 corrosion inhibiting preparations ('wet' specimens), while most of the remaining specimens were assembled 'dry', i.e. using degreased components. A few specimens were assembled with components previously coated with Bolicone "Grease 73" anti-corrosion sealing compound (Ref. 17). Table 2 summarises the 13 different joint-inhibitor combinations used in this investigation.

TABLE 2

Joint-inhibitor Combinations

High load transfer (4-piece)		Low load transfer (3-piece)	
Fully torqued bolts (tight)	Low torque bolts (loose)	Fully torqued bolts (tight)	Low torque bolts (loose)
No inhibitor (dry) LPS-3 PX-112 Bolicone sealant	No inhibitor (dry) LPS-3 PX-112 —	No inhibitor (dry) LPS-3 PX-112 —	No inhibitor (dry) LPS-3 PX-112 —

Static tensile tests were made on four bolted joint specimens and results are given in Table 3. In addition, four specimens were strain-gauged in an attempt to assess the load transfer characteristics of the different joint-inhibitor combinations. Details of these tests are given in Appendix 2.

TABLE 3

Static tensile tests on bolted joint specimens

Joint type	Failing stress, nett area (MPa)[1]
4-piece, tight, dry	479
4-piece, tight, LPS-3	479
3-piece, tight, dry	476
3-piece, tight, LPS-3[2]	476

[1]All failures were through line of outer row of bolt holes.
[2]Uncracked after $27 \cdot 08 \times 10^6$ cycles at $S_{max} = 103$ MPa.

3. FATIGUE TESTING

All fatigue tests were carried out under repeated tension ($R = +0 \cdot 1$)* with sine-wave loading in a 600 kN Tinius-Olsen electro-hydraulic servo-controlled testing machine. Two cyclic frequencies were used, namely $2 \cdot 5$ Hz and 17 Hz, the latter when the fatigue life was expected to exceed about 10^6 cycles. The specimens were clamped in hydraulic grips through soft aluminium reinforcing plates with "Screen-Bak Metalite" 320 grit abrasive cloth† interlayed between the specimen ends and the soft aluminium to reduce fretting and prevent gripping-end failures. A total of about 165 specimens were tested in this investigation.

* Stresses were always calculated on the nett area through a transverse row of holes although, in many cases, failures initiated at locations other than bolt holes in cross-sections of greater nett area. Gross/nett area ratio = $1 \cdot 33$.

† Marketed in Australia by Norton Pty. Ltd.

As a consequence of the specimen design it was expected that fatigue cracks would develop in the middle plates and adjacent to the outer row of holes at each end. When the first failure occurred in any particular specimen the four bolts at that end and the broken piece in the grips were removed. Until about half way through the investigation the area from which the bolts had been removed was simply gripped in the hydraulic grips and the test continued until failure occurred at the second end. For the latter half of the investigation steel transfer attachment plates were bolted to the first failure end before continuing the fatigue test to failure at the other end. Thus each specimen provided two test results.

Six-load range lo-hi-lo program-load tests were also carried out on a total of 23 tight specimens. These were undertaken, firstly, to determine the relative fatigue lives of wet and dry joints under loading sequences more representative of service conditions than constant-amplitude loading; and secondly, to determine whether there were major differences in the mode of failures under constant amplitude and multi-load-level loading conditions.

Load programming of the machine was achieved using an EMR 1641 profiler* operating with punched paper tape. Two different severities of spectrum were adopted, designated 'severe' and 'moderate' respectively, and these are represented by the sequences shown in Figure 2. Each sequence contained a total of 1049 cycles per program, and the load ranges were chosen to correspond with those at which constant-amplitude data had been obtained. For the five highest load ranges (1 to 5) the cyclic frequency was 2·5 Hz, while at the lowest load range (no. 6) it was 17 Hz. Program-loading tests were commenced at the lowest load range of the program.

4. TEST RESULTS

4.1 Fatigue Tests

Figures 3 to 6 show the results of the constant-amplitude fatigue tests on the 13 joint-inhibitor combinations investigated. The average S/N curves shown in Figures 3 and 5 were derived from a least squares regression analysis of the data on the assumptions of a log-normal distribution of life and that the curves could be described by polynominal functions. Second or third order curves were found to best-fit the data. Tables 4 and 5 provide statistical information relating to the fatigue test results covered in Figures 3 to 6. The results of the program-loading tests are presented in Table 6.

Although the specimens were not subjected to an aggressive corrosive atmosphere either prior to or during fatigue testing, some of the tests at the lower cyclic frequency (2·5 Hz) took over 17 days of continuous testing to complete. At the higher frequency of 17 Hz the specimen with a life of $27 \cdot 7 \times 10^6$ cycles took nearly 19 days to test. In contrast to this, the tests reported in Refs 13 and 14 were carried out at a cyclic frequency of 30 Hz, and the specimen with the longest life involved a testing time of only about 10 hours. Mousley (Ref. 14) has acknowledged that his testing conditions did not allow time—dependent effects to be represented.

4.2 Fracture Examination

At the conclusion of the fatigue testing program the specimens were disassembled to study both the fracture surfaces and the faying surfaces. The components in dry tight specimens readily separated when the bolts were removed, whereas many of the components in wet specimens were found to be stuck together and were lightly tapped to separate them. Although some of the wet specimens had been assembled almost three years beforehand, the faying surfaces previously coated with the corrosion inhibitors were still in a wet condition. It was quite evident, as shown particularly in the left hand side of Figure 7, that most of the corrosion inhibitor had been retained in the joint and that the fretting product formed during fatigue testing had dispersed into the inhibitor and spread over almost the entire faying surfaces.

All fatigue failures occurred in the middle component of the joints, i.e. components 1 or 2 in Figure 1, but at a variety of crack initiation sites. The different fatigue crack initiation regions

* Manufactured by Weston Instruments Inc., Florida, USA.

were classified using the grid system illustrated in Figure 8. Under constant-amplitude almost 100% of the loose specimens showed clear evidence of multiple crack initiation, compared with only about 70% of the tight specimens exhibiting this characteristic. Under program loading less than half of the fracture surfaces of the (tight) specimens showed evidence of multiple crack initiation.

TABLE 4

Summary of Tight Specimen Results

Test Condition	Maximum stress (S_{max})		Cyclic frequency (Hz)	Number of results	Log. mean life ($\bar{N}$)	s.d. of log life
	MPa	psi				
4-piece, tight, dry	414	60,000	2·5	6	50,700	0·034
	345	50,000	2·5	4	74,500	0·039
	310	45,000	2·5	6	124,800	0·081
	276	40,000	2·5	4	181,800	0·079
	207	30,000	2·5	6	436,500	0·050
	138	20,000	2·5	6	$1·1402 \times 10^6$	0·057
	138	20,000	17	4	$1·2671 \times 10^6$	0·115
	103	15,000	17	4	$4·5701 \times 10^6$	0·159
4-piece, tight, wet (LPS-3 and PX-112)	414	60,000	2·5	12	25,700	0·182
	310	45,000	2·5	12	114,600	0·113
	207	30,000	2·5	13	362,800	0·075
	138	20,000	2·5	6	$2·2310 \times 10^6$	0·162
	138	20,000	17	4	$2·2959 \times 10^6$	0·139
	103	15,000	17	4	$9·857 \times 10^6$	0·331
4-piece, tight, Bolicone	414	60,000	2·5	4	50,000	0·092
	207	30,000	2·5	6	320,800	0·084
	138	20,000	2·5	4	$1·2453 \times 10^6$	0·147
3-piece, tight, dry	414	60,000	2·5	6	47,200	0·074
	310	45,000	2·5	6	143,600	0·054
	207	30,000	2·5	6	428,200	0·098
	138	20,000	2·5	6	970,600	0·070
	138	20,000	17	4	$1·0166 \times 10^6$	0·047
	103	15,000	17	4	$2·7269 \times 10^6$	0·154
3-piece, tight, wet (LPS-3 and PX-112)	414	60,000	2·5	12	23,200	0·150
	310	45,000	2·5	12	118,700	0·057
	207	30,000	2·5	12	445,300	0·093
	138	20,000	2·5	6	$2·2710 \times 10^6$	0·135
	138	20,000	17	4	$2·0793 \times 10^6$	0·112
	103	15,000	17	4	$17·234 \times 10^6$	0·353

4.2.1 Constant-amplitude Tests

With four exceptions, the major fatigue cracks in all of the loose specimens originated at the edge or in the bore of the holes in the outer row of bolts (Fig. 8) at locations C2, C4,

TABLE 5

Summary of Loose Specimen Results

Test Condition	Maximum stress (S_{max})		Cyclic frequency (Hz)	Number of results	Log. mean life ($\bar{N}$)	s.d. of log. life
	MPa	psi				
4-piece, loose, dry	207 103	30,000 15,000	2·5 2·5	4 4	23,700 607,600	0·188 0·297
4-piece, loose, wet (LPS-3 and PX-112)	207 103	30,000 15,000	2·5 2·5	7 9	26,600 672,500	0·051 0·212
3-piece, loose, dry	207 103	30,000 15,000	2·5 2·5	4 4	47,700 382,200	0·085 0·197
3-piece, loose, wet (LPS-3 and PX-112)	207 103	30,000 15,000	2·5 2·5	8 10	81,200 $1 \cdot 5328 \times 10^6$	0·118 0·114

C6, C8, D2, D4, D6, or D8. Some typical examples are shown in Figure 9*. The four exceptions—all long life specimens tested at S_{max} = 103 MPa—exhibited primary origins at locations B2, B8 and E6. This type of failure is referred to in more detail later. Fretting adjacent to the hole boundaries at the two inner rows of holes is also shown in Figure 9, this being particularly heavy in 4-piece specimens. The 4-piece loose specimens also developed spots of heavy fretting on the plates between the holes—a feature which was virtually absent on the 3-piece specimens. Cracks were also detected at the *inner* rows of holes in four of the 12 3-piece loose wet specimens and one of the six 3-piece loose dry specimens, these being the only cases of cracking at that particular location.

In contrast to the failures in the loose specimens, in tight specimens primary cracking from bolt holes occurred in a *total* of only 12 instances (7 wet, 5 dry). Ten of these were from tests at the highest value of S_{max}, i.e. 414 MPa. In about half of the fractures from 4-piece tight dry specimens tested at S_{max} of either 138 or 103 MPa and in *all* of the fractures from 3-piece tight dry specimens tested at these stress levels the major cracks originated from surface fretting damage near the ends of the cover plates at lines A and F—see Figures 10(c) and 11(c). A total of only five tight wet fractures exhibited primary cracking at this location, four of these being from tests at S_{max} of either 138 or 103 MPa. They are typified in Figures 12(c) and 13(c).

With the exception of seven cases where cracks originated at bolt holes and five cases where cracks originated adjacent to the ends of the cover plates, *all* the tight wet specimen fractures developed from origins associated with fretting at the sheet surface at either lines B or E, i.e. not coincident with the holes but generally within the circular areas under the pressure cones resulting from bolt clamping which are clearly illustrated in Figures 12 and 13. Hartman *et al.* (Ref. 18) have shown that in riveted joints typical 45° fretting initiated cracks occur in the Alclad layer and that these propagate as transverse cracks into the core material. This fretting failure location in the pressure cone area also predominated in tight dry specimens (Figs 10 and 11), but some developed primary cracking from either the bolt holes or adjacent to the ends of the cover plates. The exceptions were about ten cases of failures originating at locations C1,

* It should be noted that, because of specimen symmetry, lines A and F are "equivalent", as are lines B and E, and lines C and D. Similarly, with columns 1 and 9, 2 and 8, 3 and 7, and 4 and 6.

TABLE 6

Results of Program-load Tests (programs to failure)

Test Condition	Spectrum		Ratio Moderate/severe
	Severe	Moderate	
4-piece, tight, dry	388·5	2143·5	
	647·5	2153·5	
	531·5	2313·5	
	809·5	2313·5	4·04
	527·5	2228·5	
	538·5	2431·5	
Log. mean life	559·5	2261·5	
s.d. of log. life	0·106	0·021	
4-piece, tight, wet (LPS-3)	652·5	1629·5	
	819·5	1796·5	
	684·5	2001·5	
	787·5	1765·5	
	761·5	2275·5	2·44
	947·5		
Log. mean life	769·5	1880·5	
s.d. of log. life	0·058	0·056	
3-piece, tight, dry	519·5	1673·5	
	583·5	1931·5	
	357·5	1778·5	
	598·5	2240·5	3·71
	407·5	1699·5	
	654·5	2052·5	
Log. mean life	508·5	1885·5	
s.d. of log. life	0·103	0·050	
3-piece, tight, wet (LPS-3)	716·5	1761·5	
	958·5	1841·5	
	632·5	2260·5	
	819·5	2849·5	
		2545·5	2·94
		2613·5	
Log. mean life	772·5	2275·5	
s.d. of log. life	0·078	0·085	

The 0·5 programs associated with individual results indicates that final failure occurred at the application of the maximum load of the program.

C5, C9, D1 and D9. In all the Bolicone sealant specimens the major cracking developed at lines B or E—see Figure 14.

Figures 10 to 14 also indicate a number of other characteristics associated with 'tightness' and 'wetness'. In dry tight specimens (Figs 10 and 11) the overall intensity of surface damage and fretting decreased with decreasing stress level, but this trend was less apparent in the case of wet tight specimens (Figs 12 to 14). Similarly, with decreasing stress level dry specimens showed increasing evidence of the development of "fingers" of fretting from the outer rows of holes towards the ends of the cover plates as illustrated in Figs 10(b) and (c) and 11(b) and (c). This characteristic was much less clearly defined in wet specimens. Comparing the 4-piece and 3-piece specimens, the 4-piece specimens exhibited (i) considerably greater damage or fretting surrounding the inner rows of holes (ii) isolated areas of fretting between the rows of holes and (iii) broken lines of fretting close to the inner end of one of the middle components—see, for example Figures 10(b) and 12(c). The latter was associated with slight differences in thickness (up to 0·075 mm) between the middle components of the 4-piece joints taken from different sheets of material.

4.2.2 Program-load Tests

As indicated in Section 3, program-load tests were carried out only on tight specimens. Under program loading the fractures and faying surfaces of the specimens demonstrated similar characteristics to corresponding joint-inhibitor combinations tested under the lower-stress constant-amplitude loading conditions, and there were no apparent differences in the fretting or fracture characteristics of specimens tested under the moderate or severe loading spectra.

In summary the majority of the failures under program-loading developed from areas of fretting under the pressure cones at lines B or E, but several occurred adjacent to the ends of the cover plates at lines A or F. One developed from a fretted area between the outer row of holes at location C5, while another originated at location C1. There was again marked evidence of finger-type fretting development in dry joints, compared with an almost complete absence of this feature in wet joints.

5. DISCUSSION

5.1 Pooling of Data

The fatigue data shown in Figures 3 to 6 includes (with a few exceptions resulting from equipment malfunction) both the first end failure and second end failure of every specimen. For tight specimens the ratio of the lives to first and second failures in a particular specimen ranged from 1·00 to 2·78 (with an average of 1·37 and standard deviation of 0·36); while for loose specimens the corresponding figures were: range 1·04 to 2·56, average 1·40 and standard deviation 0·40. In only eight of the 104 constant-amplitude specimens examined did the ratio of first and second lives exceed two. There was no consistent relationship between the first and second end failure of particular specimens in the range of lives at any stress level, e.g. in some cases the specimen having the lowest life to first failure had the lowest life to second failure, but in others the second failure corresponded to the longest life under that testing condition. It was considered justified to pool first and second end failures for each of the S/N curves shown in Figures 3 to 6.

At S_{max} = 138 MPa fatigue data for 4-piece and 3-piece tight dry specimens and for 4-piece and 3-piece tight wet (LPS-3) specimens were derived from tests at both 2·5 and 17 Hz. In none of the four cases was there any significant difference* in the respective lives at the two cyclic frequencies, and so in each case the data at the two frequencies were pooled.

5.2 Comparison of Inhibitors

The constant-amplitude data allowed a direct comparison to be made of the effects of LPS-3 and PX-112 corrosion inhibiting compounds on the fatigue lives of both tight and loose joints, and high and low-load transfer specimens. In no case did similar specimens incorporating

* All comparisons were made at the 5% level of significance.

either of these two inhibitors exhibit significant differences in fatigue lives and, consequently, corresponding fatigue data for the LPS-3 and PX-112 coated specimens shown in Figures 3 to 6 were pooled.

5.3 Comparison of High-load and Low-load Transfer Specimens

For the constant-amplitude tests on the types of joints used in this investigation, there is no significant difference between the fatigue lives of fully-torqued high-load transfer (4-piece) and low-load transfer (3-piece) configurations in the dry condition, nor between these two types in the wet condition. Reference to Table 8 (Appendix 2) shows that this behaviour should have been expected—at least for dry specimens—considering the apparent similarity of load transfer characteristics of the two types of joint in the areas adjacent to and outboard of the outer rows of bolt holes where the fatigue failures developed. For wet tight specimens there may be some slight differences in load transfer between 4-piece and 3-piece specimens but the data are inadequate to make any further assessment.

Table 8 indicates that the proportion of load carried by the cover plates at Gauge Station 2 in loose dry 4-piece and 3-piece specimens is markedly different, although the fatigue lives of these two types of specimens are not significantly different. The fatigue behaviour is however not surprising as, in the loose specimens, fatigue crack initiation is associated with bolt fretting in the holes. What is surprising are the significantly greater lives of 3-piece wet loose specimens compared with the corresponding 4-piece wet loose specimens and the fatigue cracking at the inner rows of holes in a number of 3-piece wet loose specimens.

5.4 Effect of Inhibitors on Fatigue Strength

5.4.1 Constant-amplitude Tests

A comparison of the dry and wet specimens constant-amplitude data shown in Figures 3 to 6 indicates that, under these loading conditions, the corrosion-inhibiting compounds investigated can cause significant changes in the lives of bolted joints.

At the highest maximum stress level employed for tight joints, i.e. S_{max} = 414 MPa—which was nearly 90% of the ultimate failing stress of the joint, the average fatigue lives of wet joints are about half those of dry joints. Initiation of major fatigue cracks in the lowest life wet specimens of both the 3-piece and 4-piece joints at the line of the bolt holes supports the view that the inhibitors can cause some reduction in the frictional force associated with clamping and, as a consequence, slip between the joint faces allows load transfer through the bolts (Ref. 19). However, the results from the strain-gauged specimens (Table 8) indicate that only in the case of the 3-piece specimens is the load carried by the cover plate at the outer row of holes reduced—and that only slightly. At intermediate stresses there are no significant differences in the lives of wet and dry tight joints, but at low maximum stresses (S_{max} = 138 and 103 MPa) the lives of wet joints (Figs 3 and 5) are significantly greater than those of dry joints, i.e. the S/N curves for the wet and dry specimens intersect—an observation also reported in Reference 16. The longer lives at low stresses are attributed to the lubricating properties of the inhibitors either in reducing the severity of the fretting on the faying surfaces (Ref. 20) or by carrying fretting products away from the fretted regions (Ref. 21) and, as a consequence, in effectively providing a more gradual change of stiffness in the transition from the centre plate to the section incorporating the cover plates. This is evidenced by the elimination of finger type fretting development found in dry specimens and the associated marked reduction in the incidence of failures originating adjacent to the ends of the cover plates—only 8% of the wet specimens compared with 65% of dry specimens at S_{max} of 138 and 103 MPa.

The fatigue tests on loose joints (Figs 4 and 6) again emphasise the serious reductions in fatigue lives (Ref. 22) which can result from inadequate clamping—by factors of at least five compared with the lives for tight joints shown in Figs 3 and 5. This behaviour is clearly associated with differences in the mode of failure in loose and tight joints. That is, the very high incidence of bolt hole initiated failures in loose specimens caused predominantly by the stress concentrating effect of the bolt hole as a result of load transfer by bolt bearing; compared with the almost complete absence of this mode of failure in tight joints in which the frictional forces caused by clamping of the bolts result in load relieving (by-passing) of the holes and a change of the failure mode to fretting initiation at the edge of the pressure cone or at other locations on the faying surfaces. The occurrence of these various failure modes in bolted and riveted joints has been discussed more fully elsewhere by Schuetz and Gerharz (Ref. 23). Compared with the tight joints the effects of the inhibitors on the fatigue life of loose joints follow a different pattern in that they have no effect on the lives of 4-piece (high-load transfer) specimens but have resulted in significant increases in the lives of 3-piece (low-load transfer) specimens—by factors of about 2 at $S_{max} = 207$ MPa and about 4 at $S_{max} = 103$ MPa. A possible explanation of this behaviour was given in the previous section.

A comparison of the 4-piece tight dry specimen results with those from similar specimens whose contacting surfaces were coated before assembly with the Bolicone sealant (Fig. 3) indicated no significant differences in the mean fatigue lives at each of the three common stress levels. However, with the Bolicone coated specimens all failures originated at lines B or E (Fig. 8) whereas, in some of the dry specimens tested at $S_{max} = 138$ MPa failures originated adjacent to the ends of the cover plates. It also follows that the fatigue lives of the Bolicone coated specimens were significantly greater than the water-displacing corrosion-inhibitor coated specimens at high stresses and significantly less at low stresses.

5.4.2 Program-loading Tests

The results of the program-loading-tests given in Table 6 indicate that under the severe spectrum the mean fatigue lives of both 3-piece and 4-piece dry specimens are significantly less than those of the respective wet specimens. Under the moderate spectrum the mean fatigue life of 3-piece dry specimens is not significantly different from that of 3-piece wet specimens. Although the mean fatigue lives of 4-piece wet and dry specimens are significantly different, this particular finding in the current tests may simply be a reflection of the relatively lower standard deviation associated with the data from 4-piece tight dry specimens tested under the moderate spectrum.

The longer mean lives of wet compared with dry specimens under the severe spectrum are somewhat surprising as the moderate spectrum had a greater proportion of low load cycles than the severe spectrum and the constant-amplitude tests indicated a beneficial effect of inhibitors on fatigue lives at low stresses. The reason for this is unknown. It may be associated with differences in the proportions of the total lives occupied in crack initiation and differences in crack propagation rates under wet and dry conditions, but the situation is undoubtedly complex because of the effect of the inhibitor solutions in changing the local frictional forces, in affecting fretting damage and the development of fretting fatigue cracks, and in penetrating between the fatigue crack fracture surfaces.

In all cases the actual fatigue lives were greater by factors of from about 2 to 3 than those predicted using the simple Palmgren-Miner Hypothesis (Table 7). Thus in this particular instance the Hypothesis has given conservative estimates of fatigue lives. Furthermore there are no significant differences in the ratio experimental/predicted lives when comparing the four ratios under severe spectrum with those obtained under the moderate spectrum; or when comparing the four ratios under each of the dry and wet conditions.

It should be pointed out that, although all of the program loading tests involved failures initiated by fretting at the sheet surfaces, some of the constant-amplitude data on which the life estimates were based involved failures which initiated at bolt holes and associated predominantly with the stress concentration at the hole. In such cases, where different failure modes occur under constant-amplitude cycling and under more complex loading sequences, further uncertainties are introduced into the use of constant-amplitude data for simple life predictions.

5.4.3 General

Water-displacing organic corrosion inhibitors can change the fatigue performance of joints by reducing the load transferred by friction and by modifying the fretting characteristics of the faying surfaces. The results of the constant-amplitude tests demonstrate that, except under very high stress conditions, the inhibitors do not have a detrimental effect on the fatique performance of double-lap bolted joints. On the contrary, at low constant-amplitude stresses (generally more applicable to service conditions), they resulted in increased fatigue lives in three

TABLE 7

Estimated Fatigue Lives, Severe and Moderate Spectra (Programs)

Load range	Log. mean life ($\overline{N}$)	Severe spectrum: Cycles per program (n)	Severe spectrum: n/N, damage per program	Severe spectrum: Damage (%)	Moderate spectrum: Cycles per program (n)	Moderate spectrum: n/N, damage per program	Moderate spectrum: Damage (%)
4-piece, tight, dry							
1	50,700	1	0·000020	0·52	1	0·000020	1·40
2	74,500	112	0·001503	38·78	28	0·000376	26·28
3	181,900	248	0·001363	35·17	62	0·000341	23·83
4	436,500	314	0·000719	18·55	138	0·000316	22·08
5	$1 \cdot 1894 \times 10^6$	304	0·000256	6·60	320	0·000269	18·80
6	$4 \cdot 5706 \times 10^6$	70	0·000015	0·39	500	0·000109	7·62
		Σ n/N = 0·003876			Σ n/N = 0·001431		
		Predicted life = 258			Predicted life = 699		
Ratio	experimental / predicted	(559·5) / (258) = 2·17			(2261·5) / (699) = 3·24		
4-piece, tight, wet (LPS-3)							
1	21,400	1	0·000047	1·10	1	0·000047	3·30
2	70,000	112	0·001600	37·35	28	0·000400	28·11
3	150,000	248	0·001653	38·59	62	0·000413	29·02
4	373,000	314	0·000842	19·65	138	0·000370	26·00
5	$2 \cdot 2567 \times 10^6$	304	0·000135	3·15	320	0·000142	9·98
6	$9 \cdot 8570 \times 10^6$	70	0·000007	0·16	500	0·000051	3·58
		Σ n/N = 0·004284			Σ n/N = 0·001423		
		Predicted life = 233			Predicted life = 703		
Ratio	experimental / predicted	(769·5) / (233) = 3·30			(1880·5) / (703) = 2·67		
3-piece, tight, dry							
1	47,200	1	0·000021	0·64	1	0·000021	1·50
2	105,000	112	0·001067	32·52	28	0·000267	19·09
3	220,000	248	0·001127	34·35	62	0·000282	20·16
4	428,200	314	0·000733	22·34	138	0·000322	23·02
5	988,700	304	0·000307	9·36	320	0·000324	23·16
6	$2 \cdot 7269 \times 10^6$	70	0·000026	0·79	500	0·000183	13·08
		Σ n/N = 0·003281			Σ n/N = 0·001399		
		Predicted life = 305			Predicted life = 715		
Ratio	experimental / predicted	(508·5) / (305) = 1·67			(1885·5) / (715) = 2·64		
3-piece, tight, wet (LPS-3)							
1	21,100	1	0·000047	1·17	1	0·000047	3·56
2	70,000	112	0·001600	39·93	28	0·000400	30·30
3	170,000	248	0·001459	36·41	62	0·000365	27·65
4	414,000	314	0·000758	18·92	138	0·000333	25·23
5	$2 \cdot 1923 \times 10^6$	304	0·000139	3·47	320	0·000146	11·06
6	$17 \cdot 234 \times 10^6$	70	0·000004	0·10	500	0·000029	2·20
		Σ n/N = 0·004007			Σ n/N = 0·001320		
		Predicted life = 250			Predicted life = 757		
Ratio	experimental / predicted	(772·5) / (250) = 3·09			(2275·5) / (757) = 3·01		

of the four load transfer—bolt clamping conditions investigated. Both 3-piece and 4-piece wet joints had longer fatigue lives under severe spectrum loading than dry joints, but under the moderate spectrum the mean life of 4-piece wet joints was significantly less than that of the 4-piece dry joints.

The findings of this investigation on bolted joints are generally in marked contrast to that reported in References 13 and 14 from constant-amplitude tests on single-lap riveted joints where it was concluded that joints incorporating water displacing organic corrosion inhibitors have mean fatigue lives of from 33% to 50% of those of untreated joints; but agree with those of Schijve *et al.* (Ref. 15) on 'dry' and LPS-3 coated symmetric double-lap riveted joints tested under a flight-by-flight loading sequence from which it was concluded that inhibitors have little affect on the life of such joints. In addition to recognising the significant differences in the joint design and construction between the current and previous investigations it should be emphasised that for the constant-amplitude investigations on riveted joints (Refs 13, 14) the mean fatigue lives did not exceed 650,000 cycles, whereas it was at longer mean lives in the current investigation that the beneficial effects of the inhibiting compounds were evident.

It is thus apparent that any generalisations relating to the effects of water displacing organic corrosion inhibitors on the fatigue behaviour of joints may not be justified. Considerations of their influence must take into account the design and type of construction of the joint (particularly its load transfer characteristics), and the severity of the fatigue loading sequence to which such 'inhibited' joints are likely to be subjected.

Finaly, a comment should be made about the scatter in fatigue lives. Reference to Table 4 shows that the standard deviation of log life are quite low although the data were pooled to include the first and second failures of particular specimens. The relatively high value of standard deviation associated with tight wet specimens at $S_{max} = 414$ MPa reflects the occurrence of failure origins both at and away from the bolt holes under these particular testing conditions. The greater scatter in life of wet specimens compared with dry specimens tested at 17 Hz at $S_{max} = 103$ MPa may simply be associated with the significantly greater mean lives of the wet specimens. This dependence of scatter on the value of mean life has been discussed elsewhere (Ref. 24).

6. CONCLUSIONS

1. The fatigue lives of double-lap bolted joints incorporating either of the water-displacing corrosion-inhibitors LPS-3 or PX-112 are not significantly different.

2. Under constant-amplitude testing there are no significant differences in fatigue lives between high-load transfer and low-load transfer fully-torqued bolted joints when compared in the dry condition or when compared in the wet condition.

3. For fully-torqued bolted joints the water-displacing inhibitors have a detrimental effect on the fatigue lives at high constant-amplitude stresses. presumably because they reduce the ability of the joints to transfer load by friction. However, at low stresses the fatigue lives of joints coated with the inhibitors are superior to those of dry joints. This has been attributed to a change introduced in the load transfer and fretting characteristics at the joint interfaces.

4. In both the dry and wet conditions the constant-amplitude fatigue lives of joints assembled with low bolt clamping forces are significantly less than similar joints assembled with fully-torqued bolts.

5. Constant-amplitude tests on joints assembled with low bolt clamping forces have shown that the fatigue lives of wet, low-load transfer (3-piece) joints are significantly greater than those of dry joints (by up to a factor of 4). This is in contrast to the results from similarly clamped high-load transfer (4-piece) joints where there are no significant differences in lives between wet and dry joints.

6. Under multi-load-level tests to a 'severe' spectrum the mean fatigue lives of both low and high-load-transfer joints incorporating the corrosion inhibitor are significantly greater than those of dry joints.

7. Under a 'moderate' spectrum the results are inconsistent. The mean fatigue lives of the wet high-load-transfer joints are significantly less than those of the dry high-load-transfer joints, whereas, for the low-load-transfer joints, there is no significant difference between the mean lives of wet and dry joints.

8. The specific effects of a water-displacing organic corrosion inhibitor on the fatigue strength of joints will be dependent on the design and construction of the joint and the severity of the loading spectrum involved.

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APPENDIX 1

Specimen Manufacture and Assembly

Before cutting for the manufacture of specimens a protective coating was applied to both sides of the alclad aluminium alloy sheets. For the first two sheets (FC1 and FC2) the coating consisted of a layer of brown paper stuck to the surface of the metal with molten lanolin. The third sheet (FC3) was covered with a self-adhesive clear plastic film of the type often used to cover books.

Specimen components were sawn from the sheet material according to the cutting plan shown in Figure 15 and then machined to size. The bolt holes in the component blanks were then drilled undersize (approx. 0·4 mm) in a jig and reamed to finished size. The assembly procedure for the specimens was as follows:

(i) Protective coating stripped off and components vapour degreased in a trichloroethylene bath.

(ii) Bolt holes deburred by lightly rubbing with A600 grit wet and dry paper using water as a lubricant, and any edge burrs removed by light chamfering.

(iii) Components thoroughly washed with water, then ethanol and dried. Bolts, nuts and washers cleaned in an ultrasonic cleaning bath and dried.

(iv) Components assembled into specimens. For wet specimens the assembly sequence is indicated in Figure 16. The procedure for dry specimens was identical except for the omission of the brushing-on of the corrosion inhibitor. In an effort to standardise nut friction on the bolt threads, care was taken to ensure that the bolt threads were kept clean. However, for every specimen (both wet and dry) the nut threads were lightly lubricated with corrosion inhibitor before attaching the nuts to the bolts.

(v) Nuts were tightened using a torque wrench, either to a torque of 27 Nm (240 pound inches) including approximately 6 Nm (50 pound inches) to form the thread in the nylon insert for the tight joints; or tightened to exert virtually no clamping force, in the case of loose joints.

APPENDIX 2

Measurement of Load Transfer Characteristics of Specimens

In an attempt to gain some quantitative information on the different load transfer characteristics of the 3-piece and 4-piece specimens assembled tight or loose, with or without corrosion inhibitor, four specimens were strain-gauged at positions shown in Figure 17. Because only four pairs of gauges were applied per specimen and the measuring equipment available could only record the output of one pair of gauges at a time the information obtained was limited. A much more comprehensive investigation on similar types of specimens is reported in Reference 25.

The strain gauge readings were dynamic measurements recorded after cycling the specimens for a maximum of five minutes at a frequency of 0·5 Hz at the selected value of S_{max}. The results are presented in Table 8, with loads carried by the cover plates at gauge stations 2, 3 and 4 being expressed as a percentage of the load at gauge station 1.

These results confirmed the expectation of differences in load transfer characteristics between 4-piece (high-load transfer) and 3-piecc (low-load transfer) specimens both in the tight and loose conditions. At stations 3 and 4 the cover plates of the 3-piece specimens carried less load than did the cover plates of the 4-piece specimens in all cases. This difference was particularly marked in the loose condition. At station 2, the differences between cover-plate strains in 3-piece and 4-piece specimens was very much less.

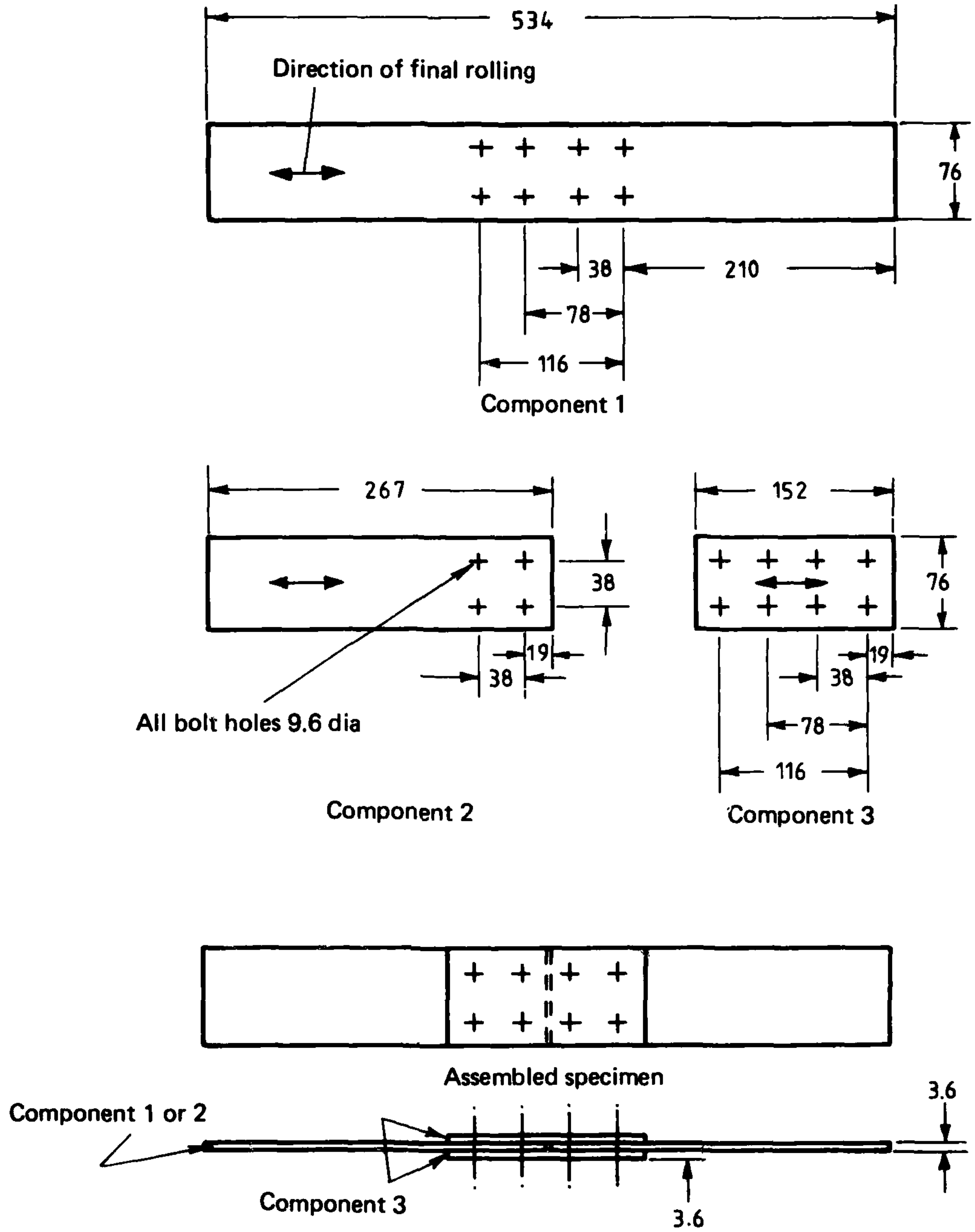
Differences in load transfer characteristics of similar specimens in the dry and wet conditions are more difficult to discern. It might be postulated that in a wet joint the coefficient of friction between the faying surfaces should be less and that this would tend to reduce the rate of load transfer from the centre component to the cover plates, i.e. the strain at gauge station 2 should be less for a wet joint than for a dry joint. To a minor extent the strain gauge results support this view, but the data obtained were not adequate for positive confirmation.

TABLE 8

Results from Strain-gauged Specimens

Gauged specimen			A	B	C	D
Specimen type	Nett stress (MPa)	Gauge station	Load (% of that at Station 1)			
			4-piece		3-piece	
			Dry	Wet	Dry	Wet
Tight	414	1	100	100	100	100
		2	30	28	26	18
		3	78	80	60	56
		4	82	98	68	66
	207	1	100	100	100*	100
		2	32	28	30	24
		3	78	80	62	62
		4	82	82	68	68
Loose	207	1	100	100	100	100
		2	24	22	2	8
		3	84	88	10	16
		4	102	112	16	12

* Specimen cycled for about 3,500 cycles before strain gauge readings; all other cases about 150 cycles at 0·5 Hz.



Bolts – AN6–10A
Nuts – MS20365–624A
Washers – AN960–616

High load transfer joint – 2 of component 2, 2 of component 3
Low load – transfer joint – 1 of component 1, 2 of component 3

All dimensions in mm

FIG. 1. BOLTED JOINT FATIGUE SPECIMENS

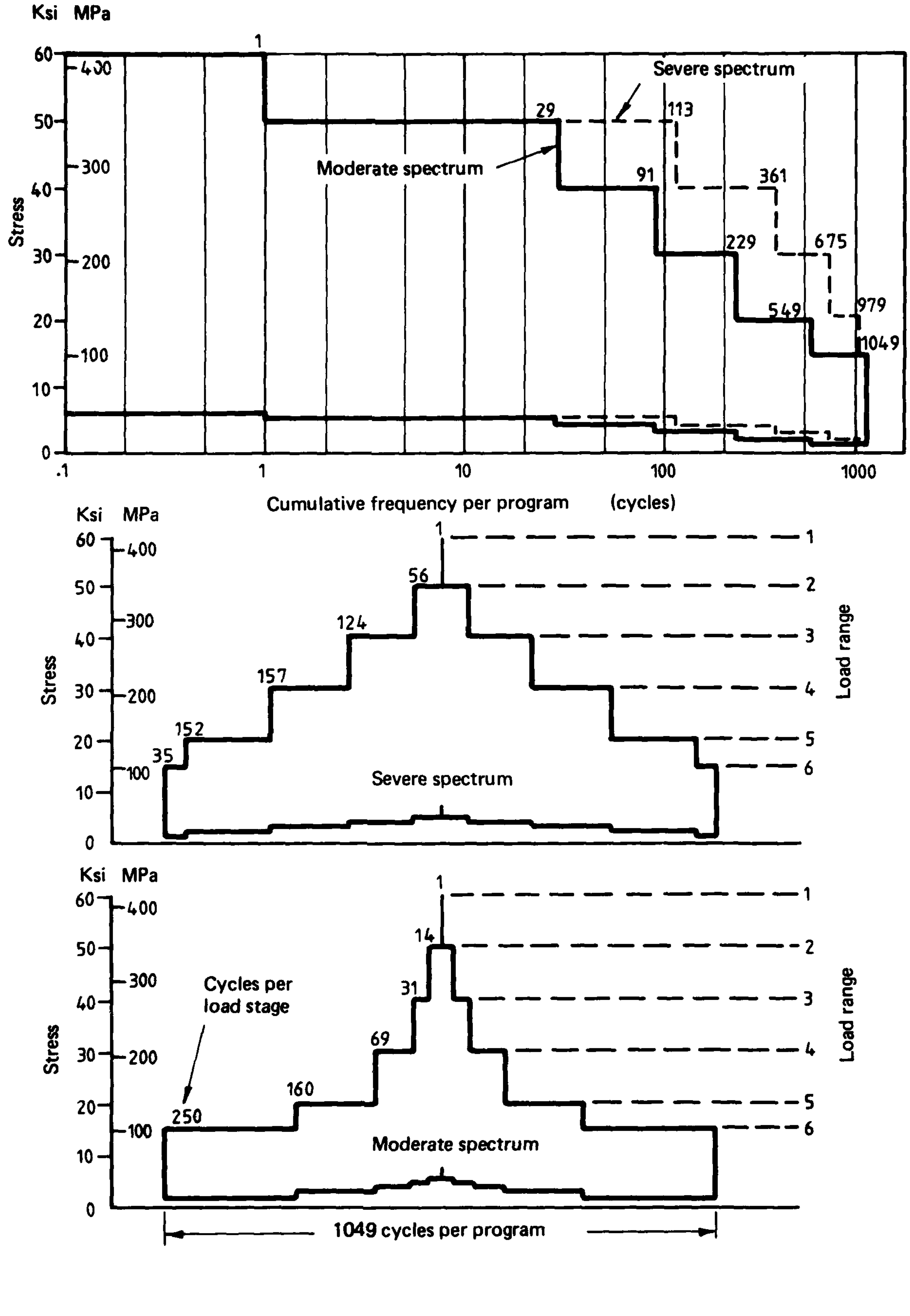


FIG. 2. SEVERE AND MODERATE STRESS SPECTRA

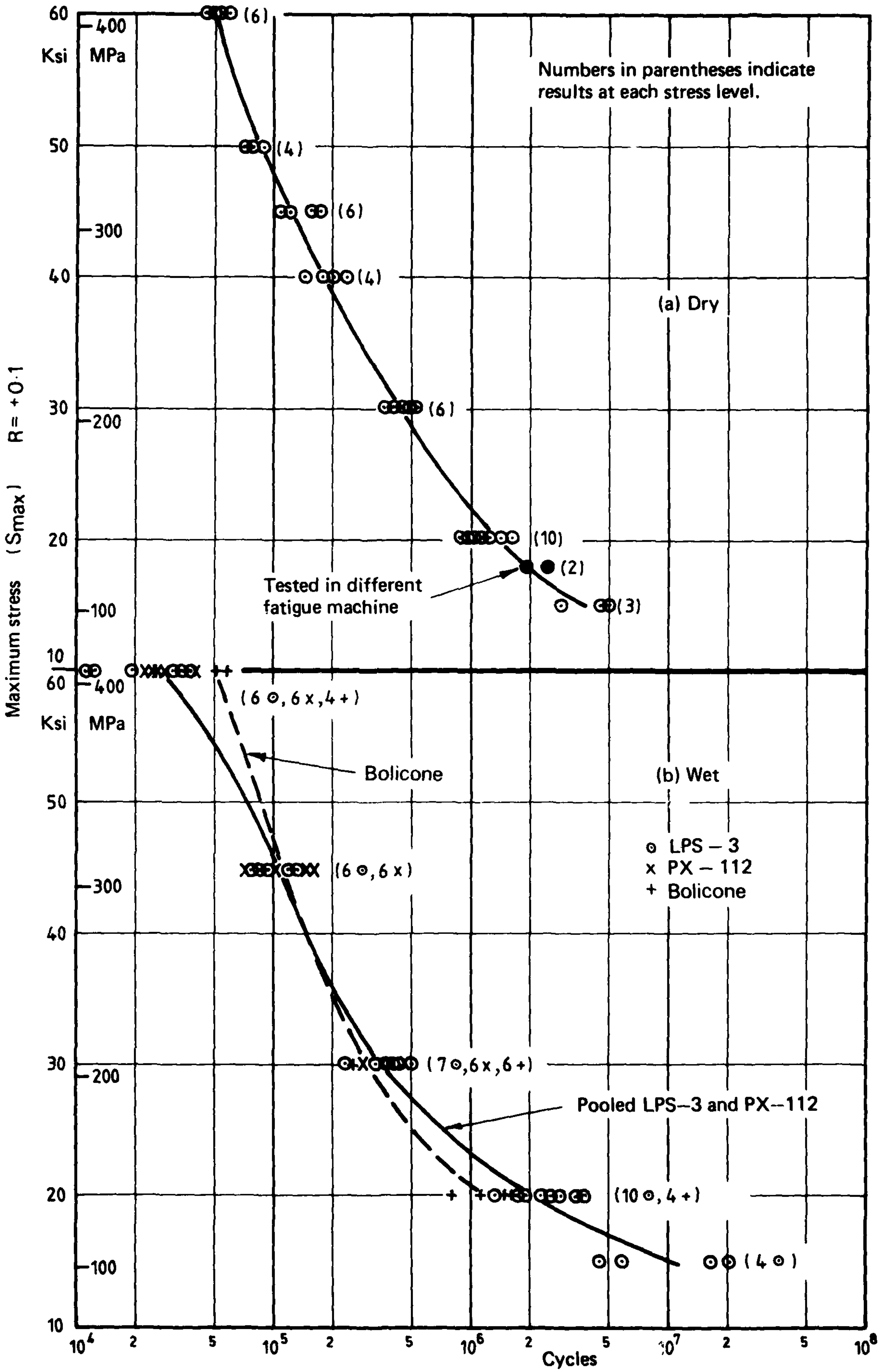


FIG. 3. 4–PIECE, TIGHT SPECIMENS

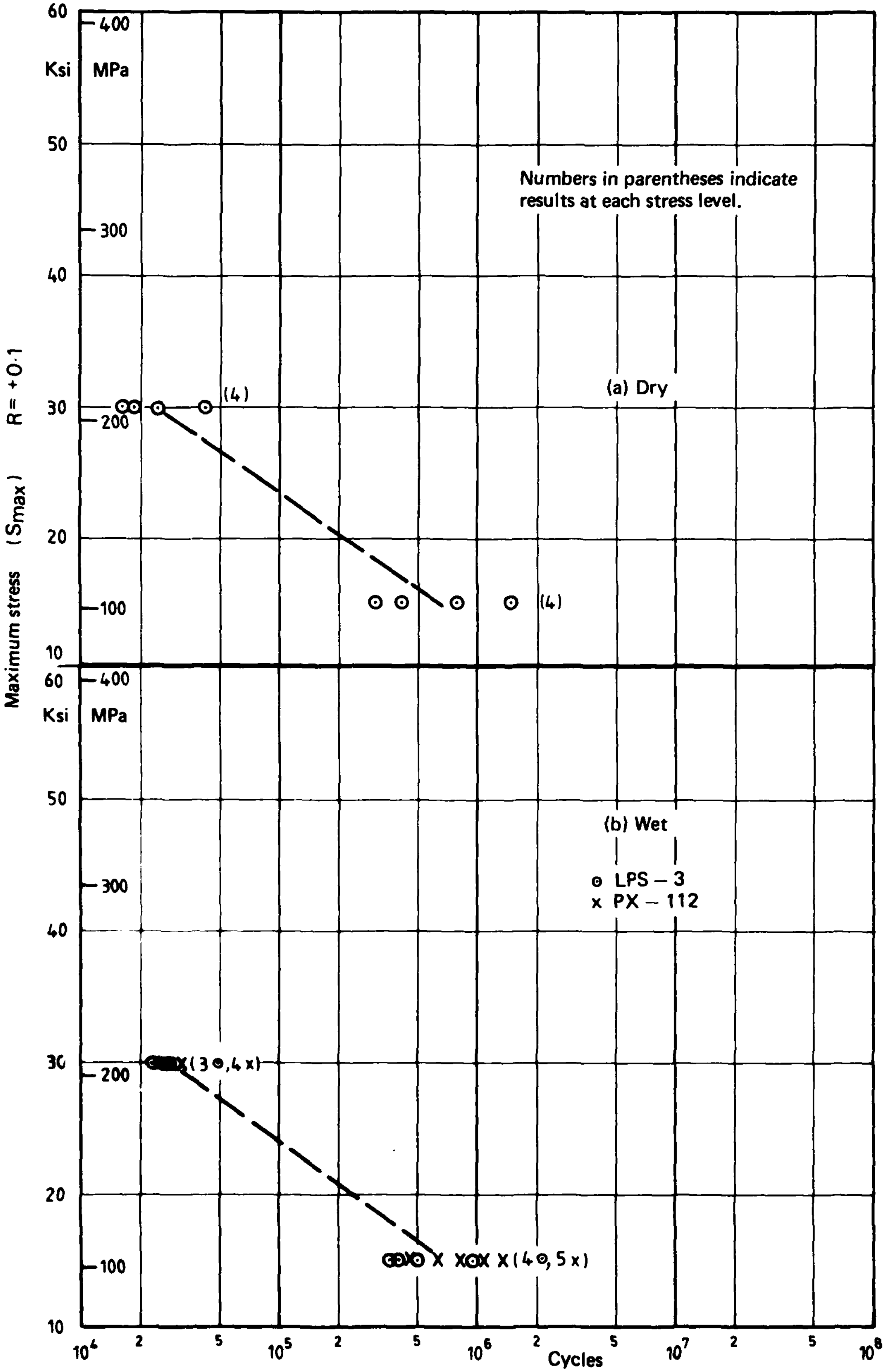


FIG. 4. 4–PIECE, LOOSE SPECIMENS

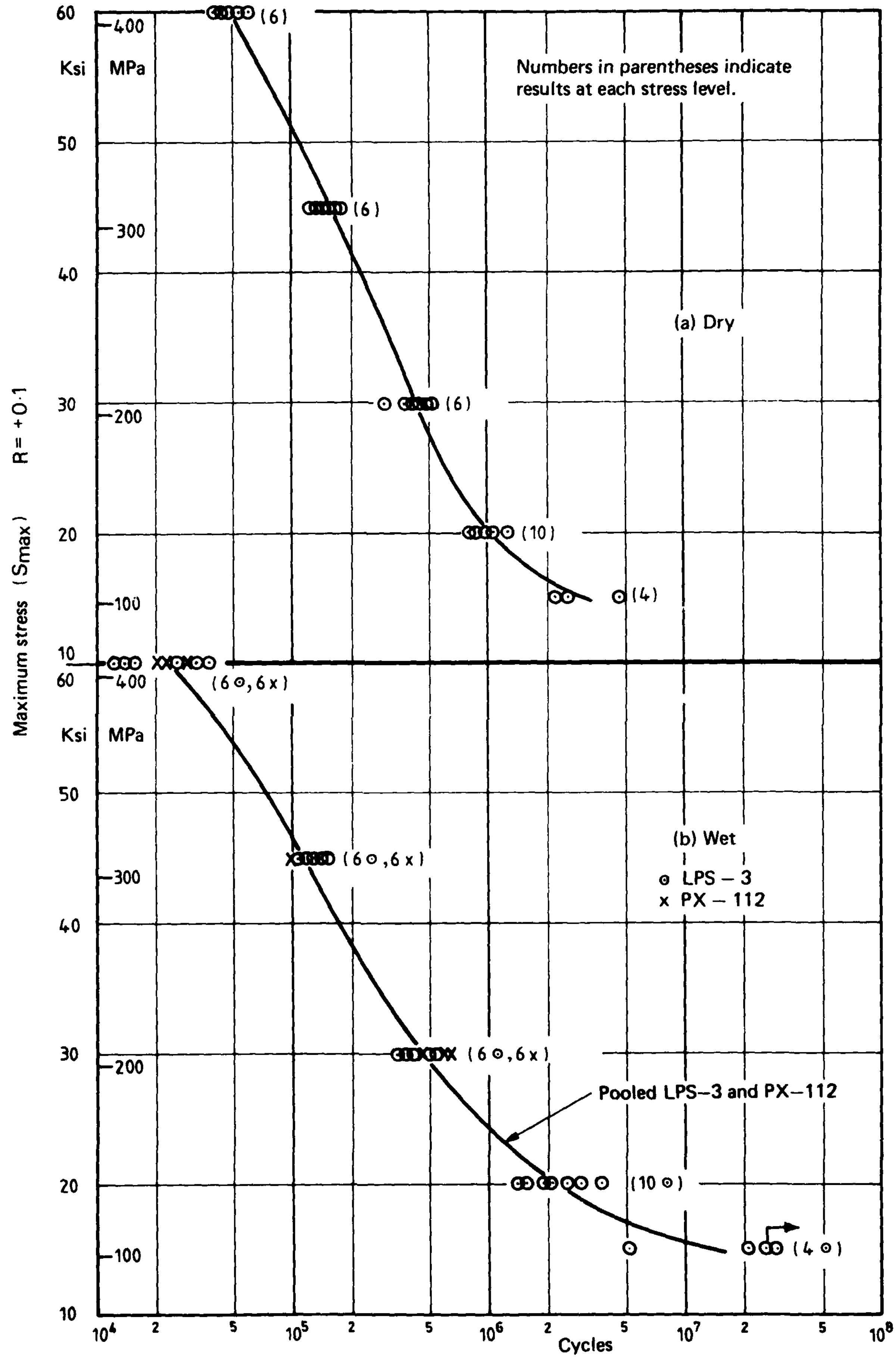


FIG. 5. 3–PIECE, TIGHT SPECIMENS

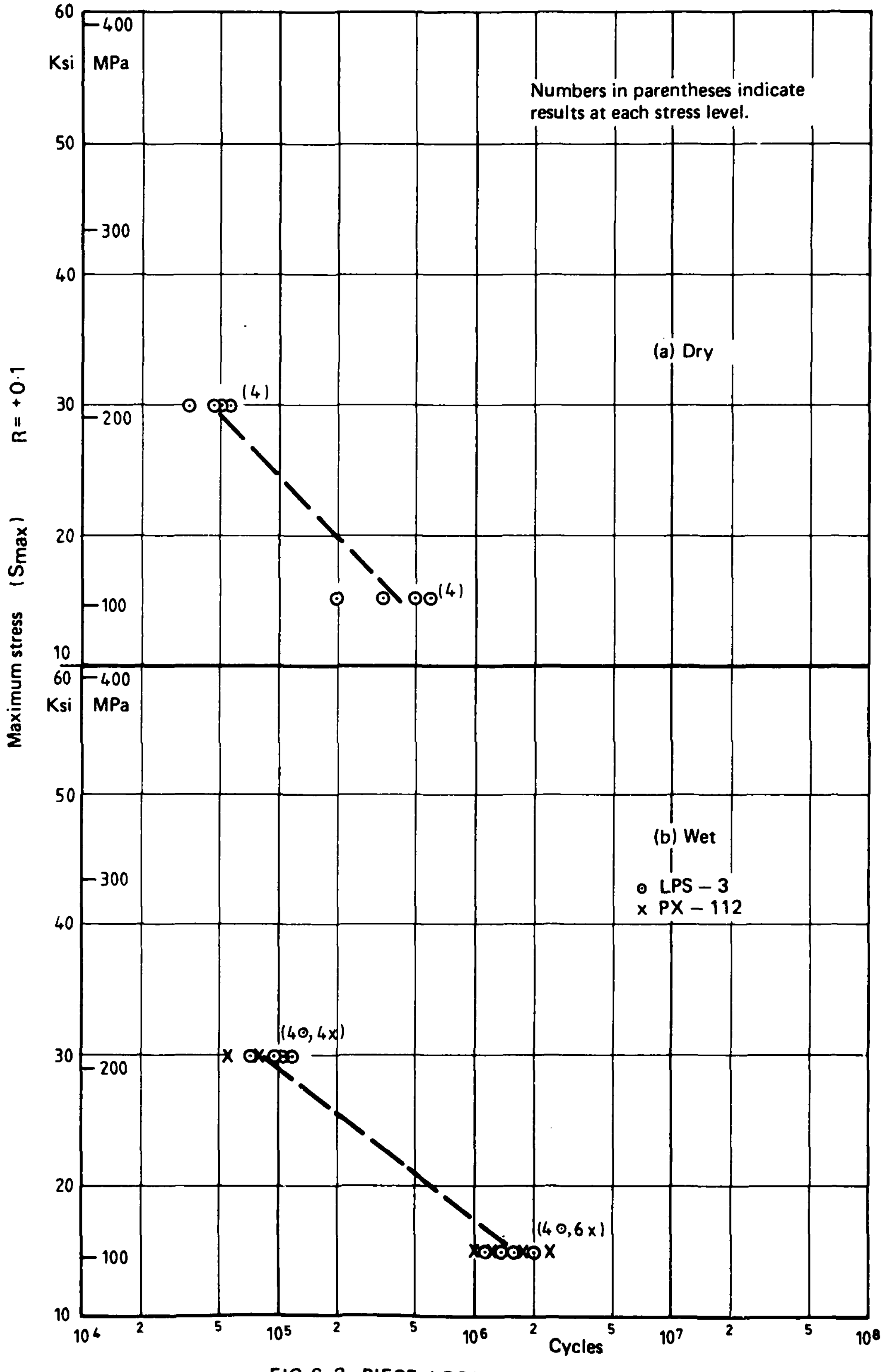


FIG. 6.3—PIECE, LOOSE SPECIMENS

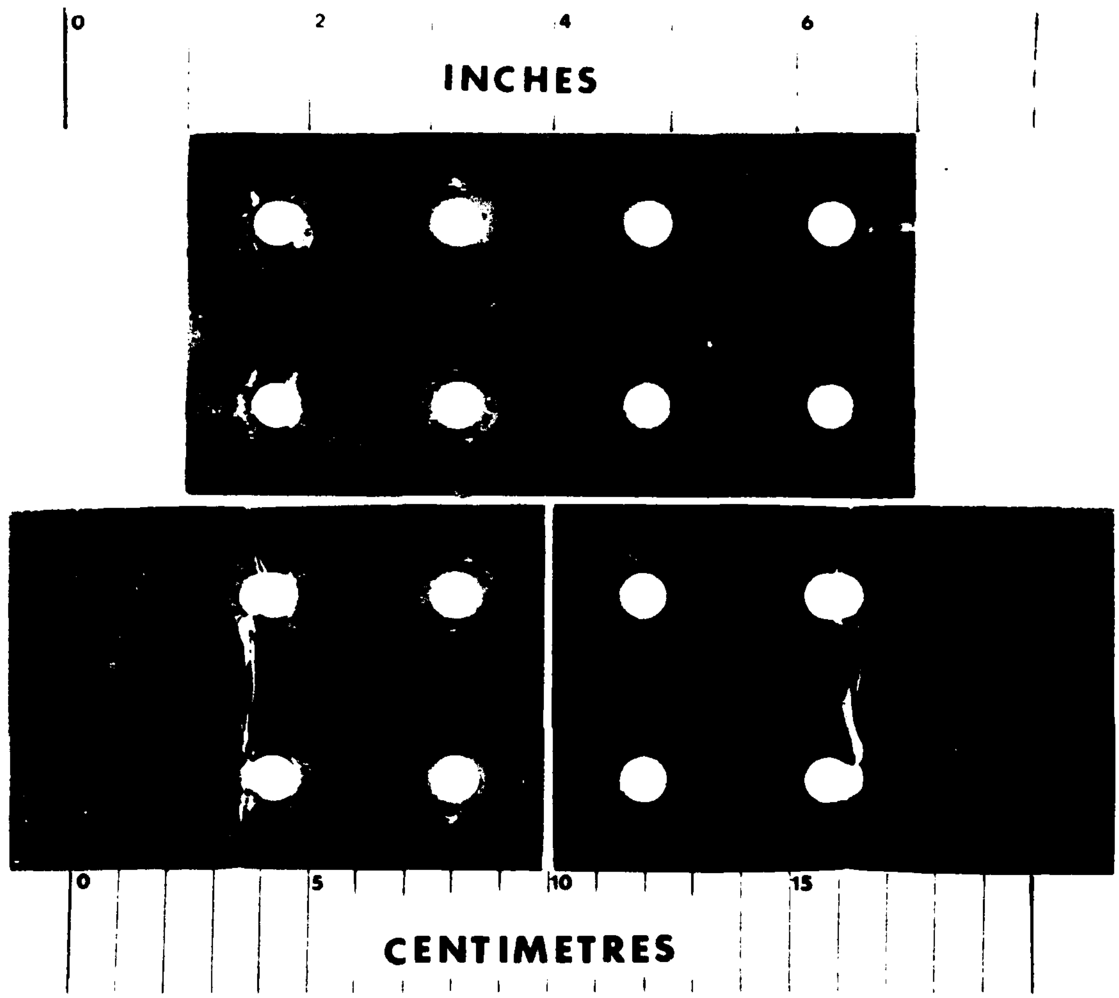
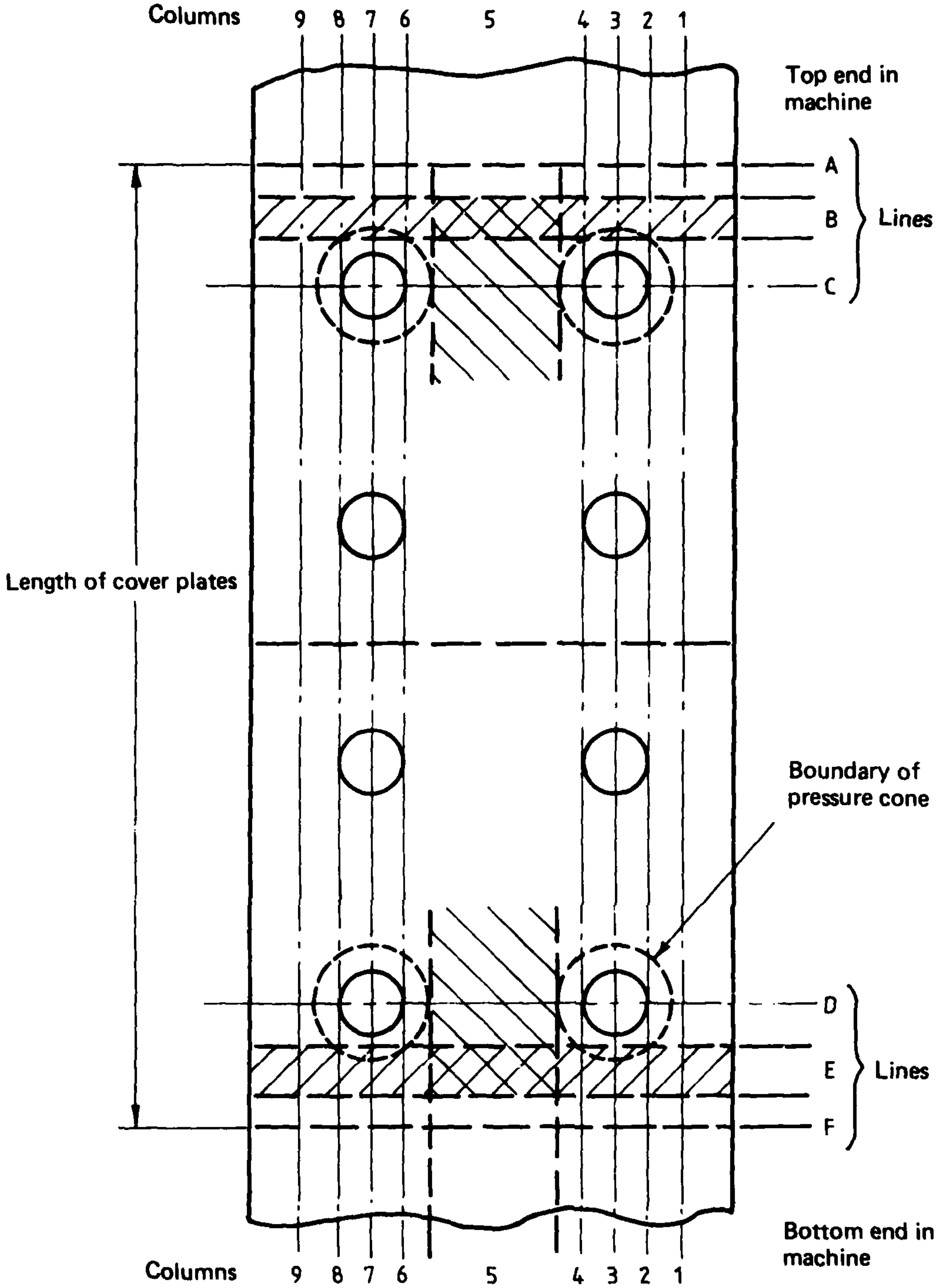


FIG. 7. 4–PIECE TIGHT WET (LPS-3)
SPECIMEN AI–114. S_{max} = 414 MPa

(Note: Some loss of inhibitor occurred after fracture and during reclamping of right hand end of this specimen)



Lines A and F – adjacent to ends of cover plates
Lines B and E – adjacent to boundary of pressure cones resulting from bolt clamping
Lines C and D – on (or close to) centreline of end rows of bolt holes.

(Using "east" face of specimens as a reference)

FIG. 8. LOCATIONS OF FATIGUE CRACKING

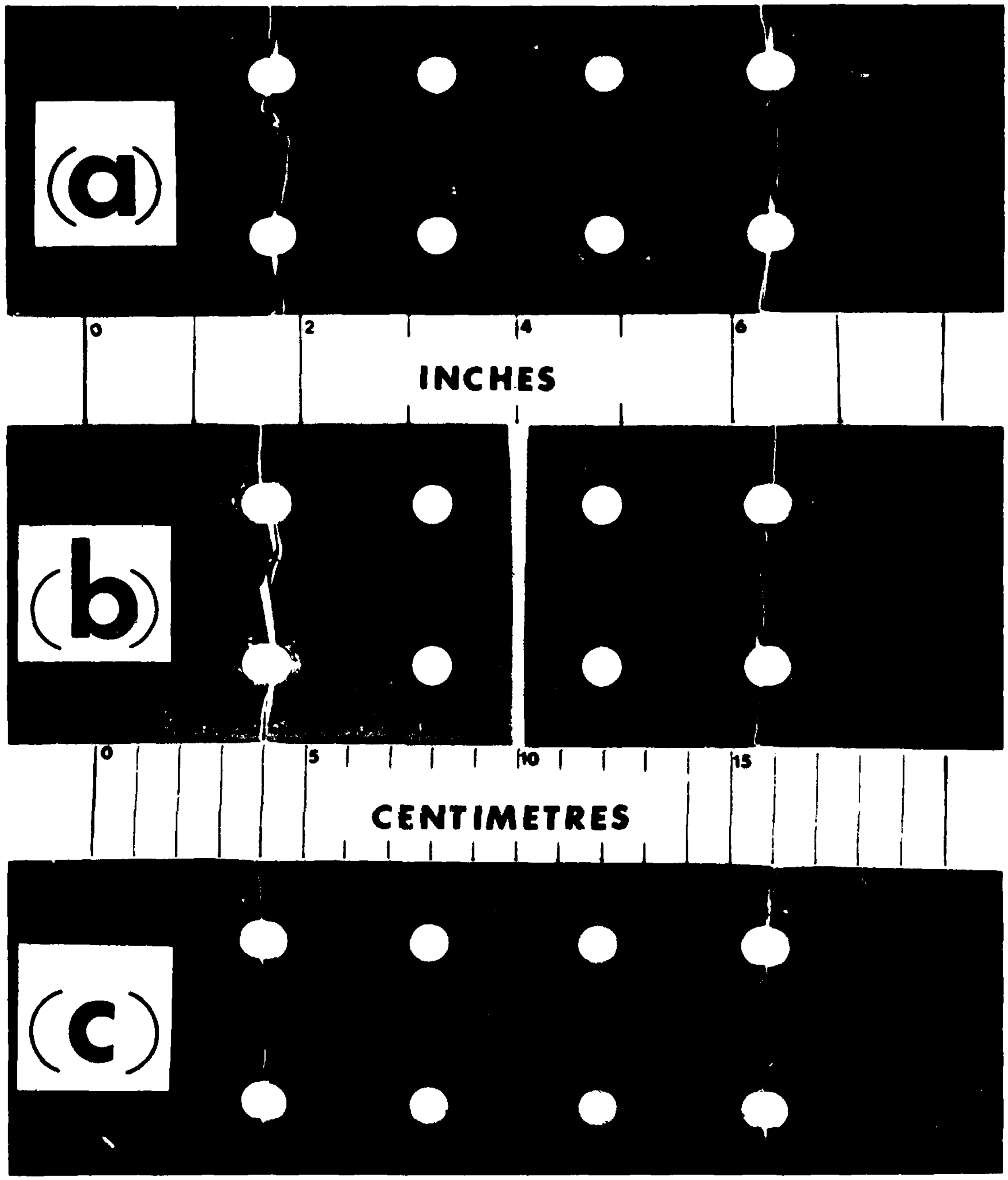


FIG. 9. FRACTURES IN LOOSE SPECIMENS

(a) 3–piece dry specimen Al–112. S_{max} = 207 MPa
(b) 4–piece dry specimen Al–147. S_{max} = 207 MPa
(c) 3–piece wet (LPS–3) specimen Al–122. S_{max} = 207 MPa

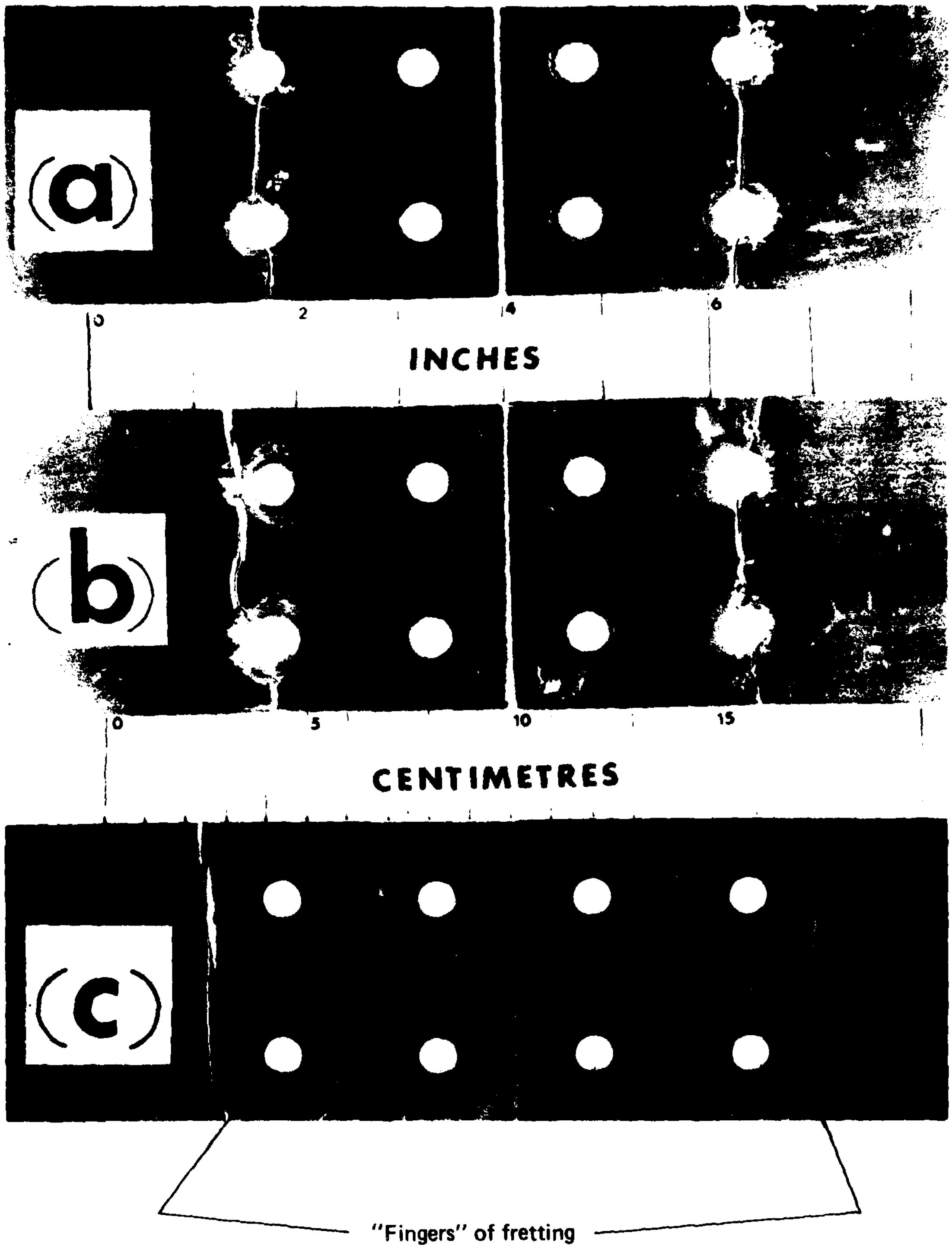


FIG. 10. 4–PIECE TIGHT DRY SPECIMEN FRACTURES

(a) Specimen no. Al–7, S_{max} = 345 MPa
(b) Specimen no. Al–8, S_{max} = 276 MPa
(c) Specimen no. Al–133, S_{max} = 103 MPa

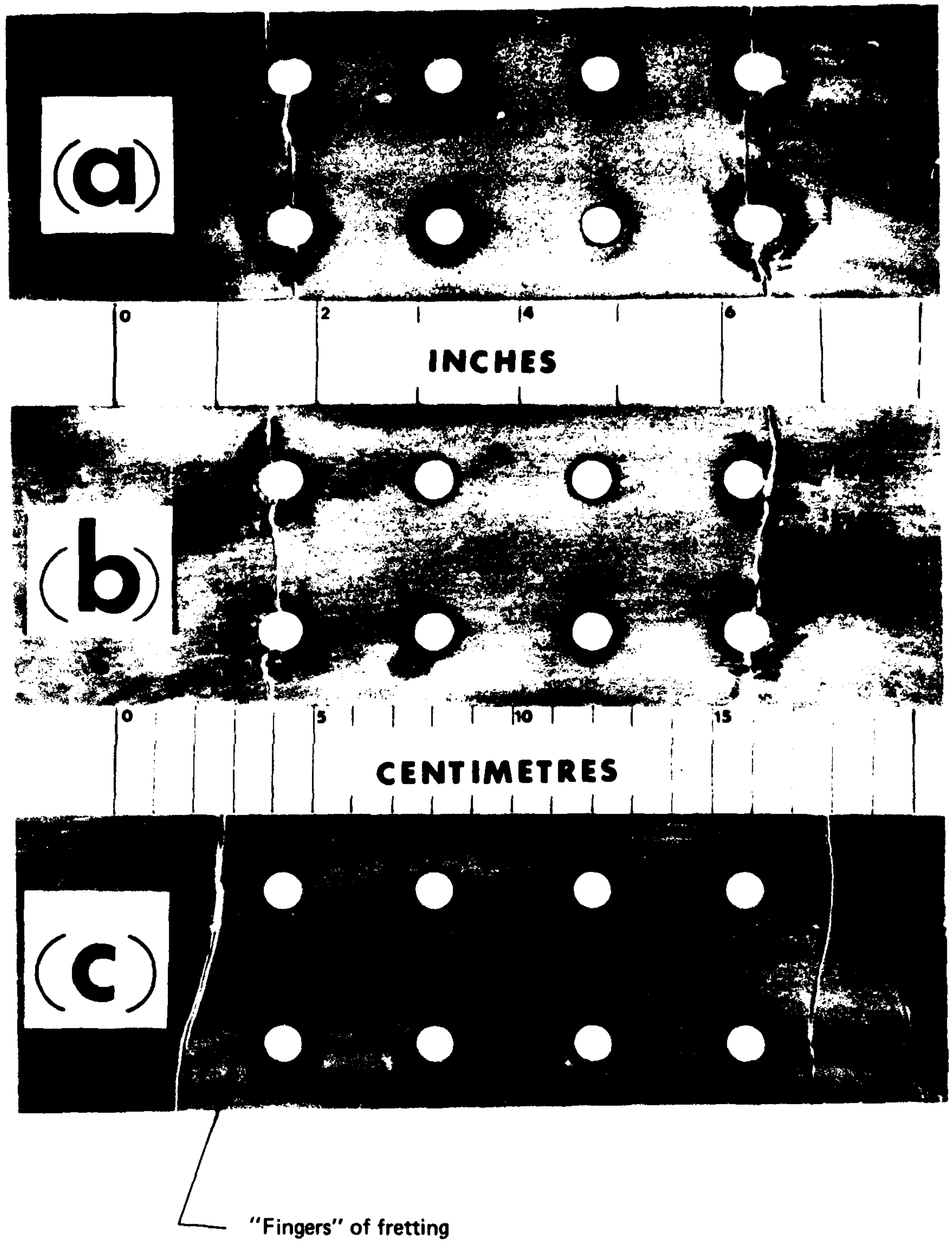


FIG. 11. 3–PIECE TIGHT DRY SPECIMEN FRACTURES

(a) Specimen no. Al–16, S_{max} = 414 MPa
(b) Specimen no. Al–26, S_{max} = 207 MPa
(c) Specimen no. Al–60, S_{max} = 138 MPa

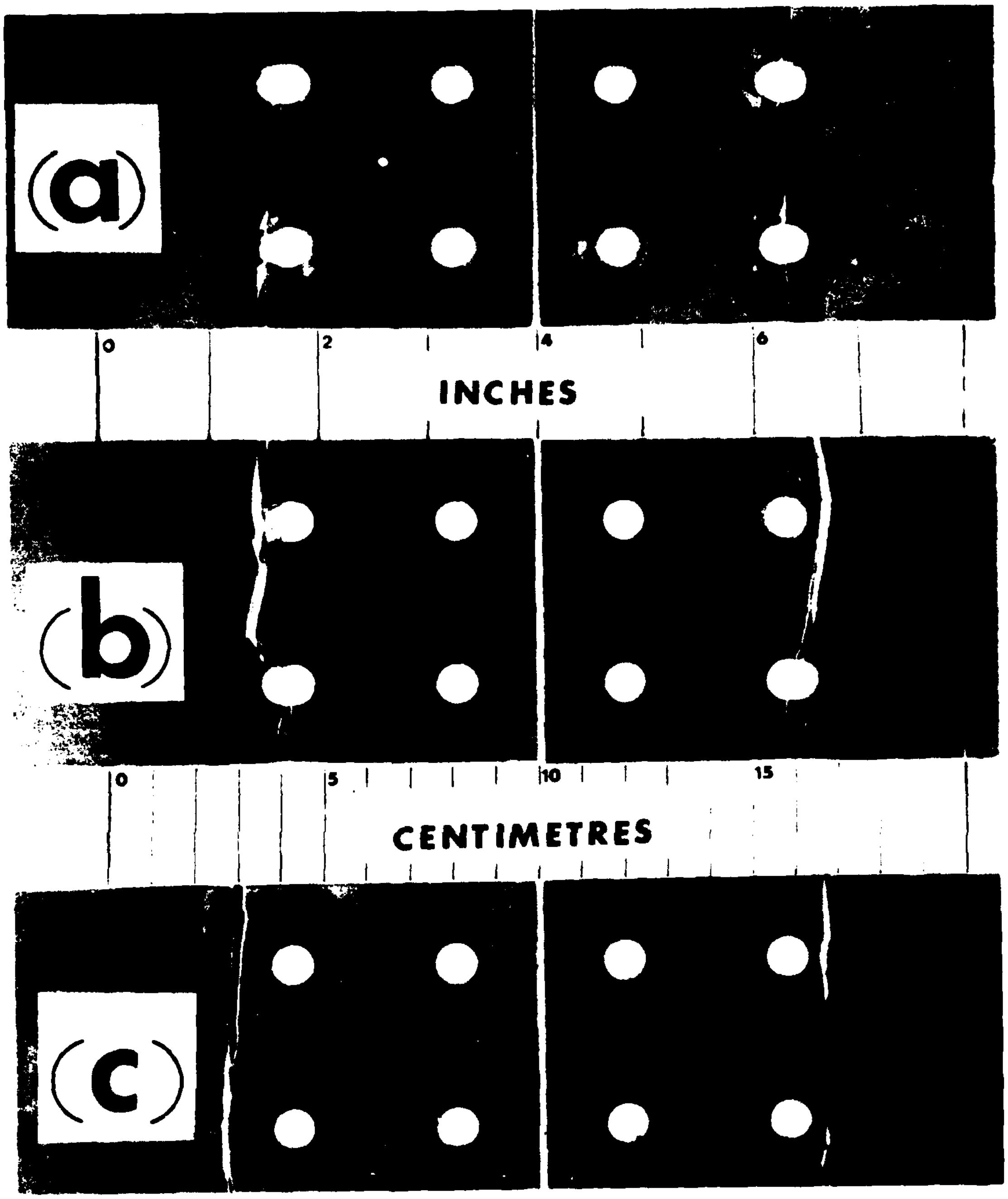


FIG. 12. 4–PIECE TIGHT WET (LPS–3)
SPECIMEN FRACTURES

(a) Specimen no. Al–29, S_{max} = 414 MPa
(b) Specimen no. Al–17, S_{max} = 207 MPa
(c) Specimen no. Al–139, S_{max} = 103 MPa

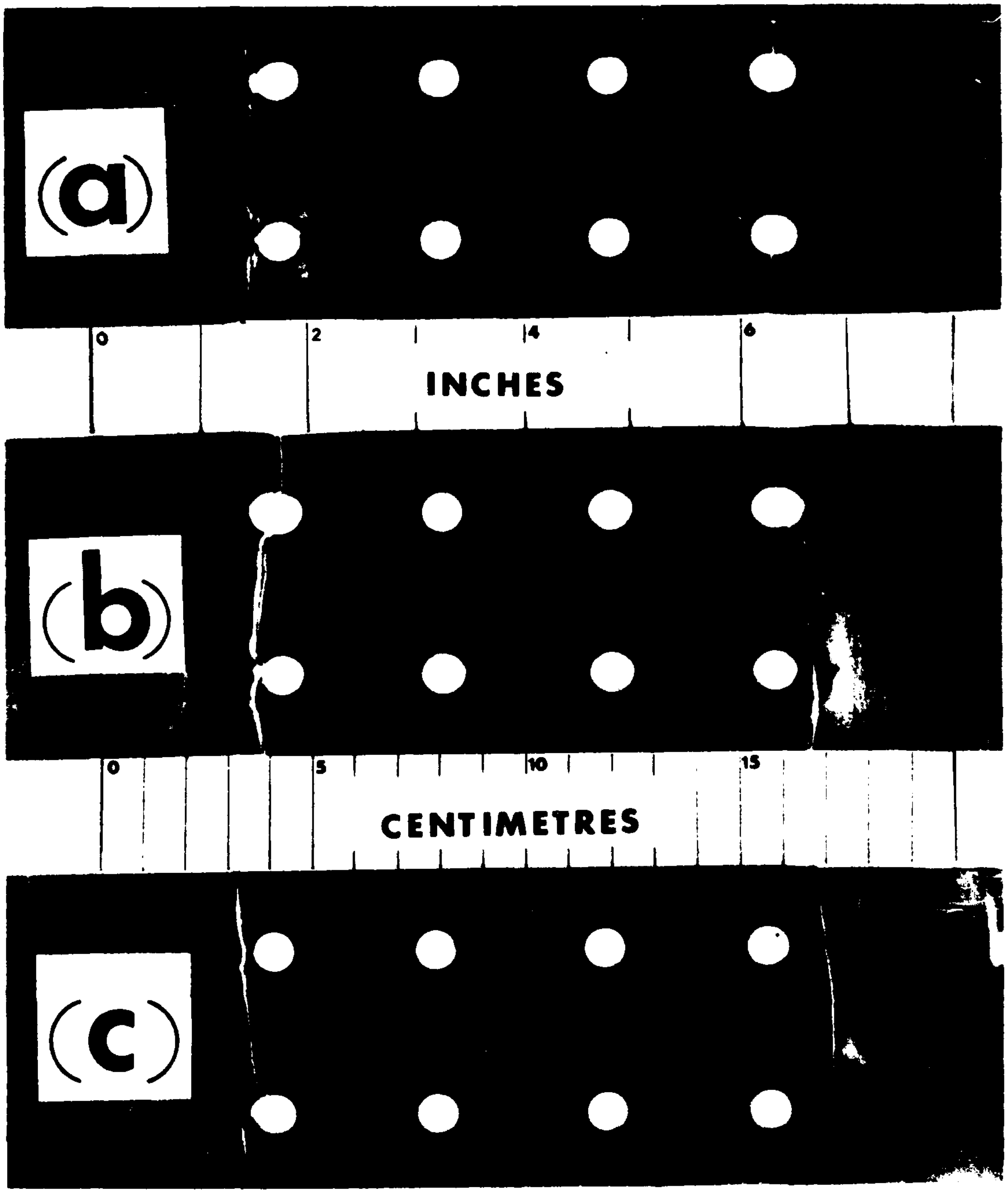


FIG. 13. 3–PIECE TIGHT WET (LPS–3)
SPECIMEN FRACTURES

(a) Specimen No. Al–28, S_{max} = 414 MPa
(b) Specimen No. Al–23, S_{max} = 207 MPa
(c) Specimen No. Al–95, S_{max} = 138 MPa

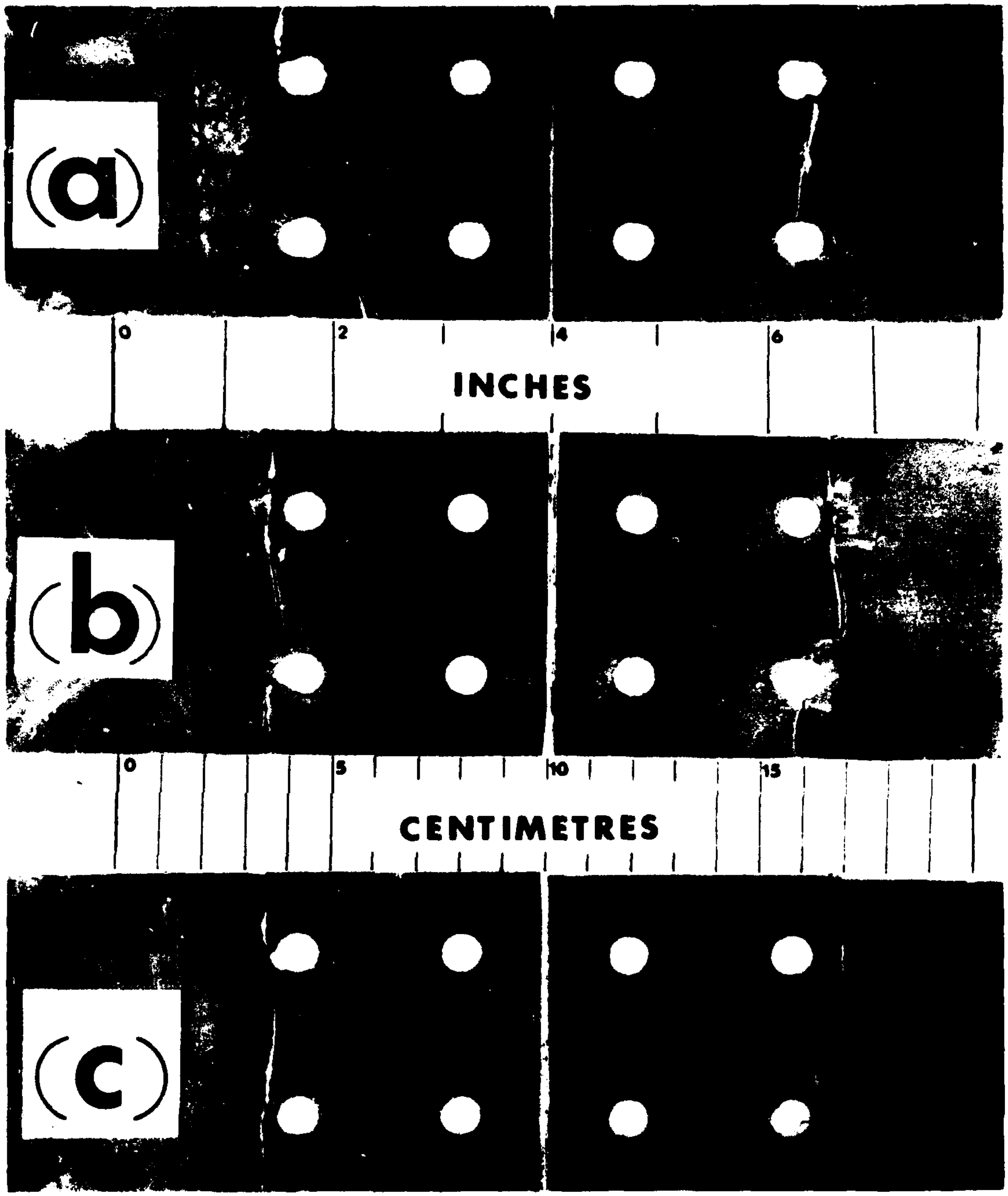
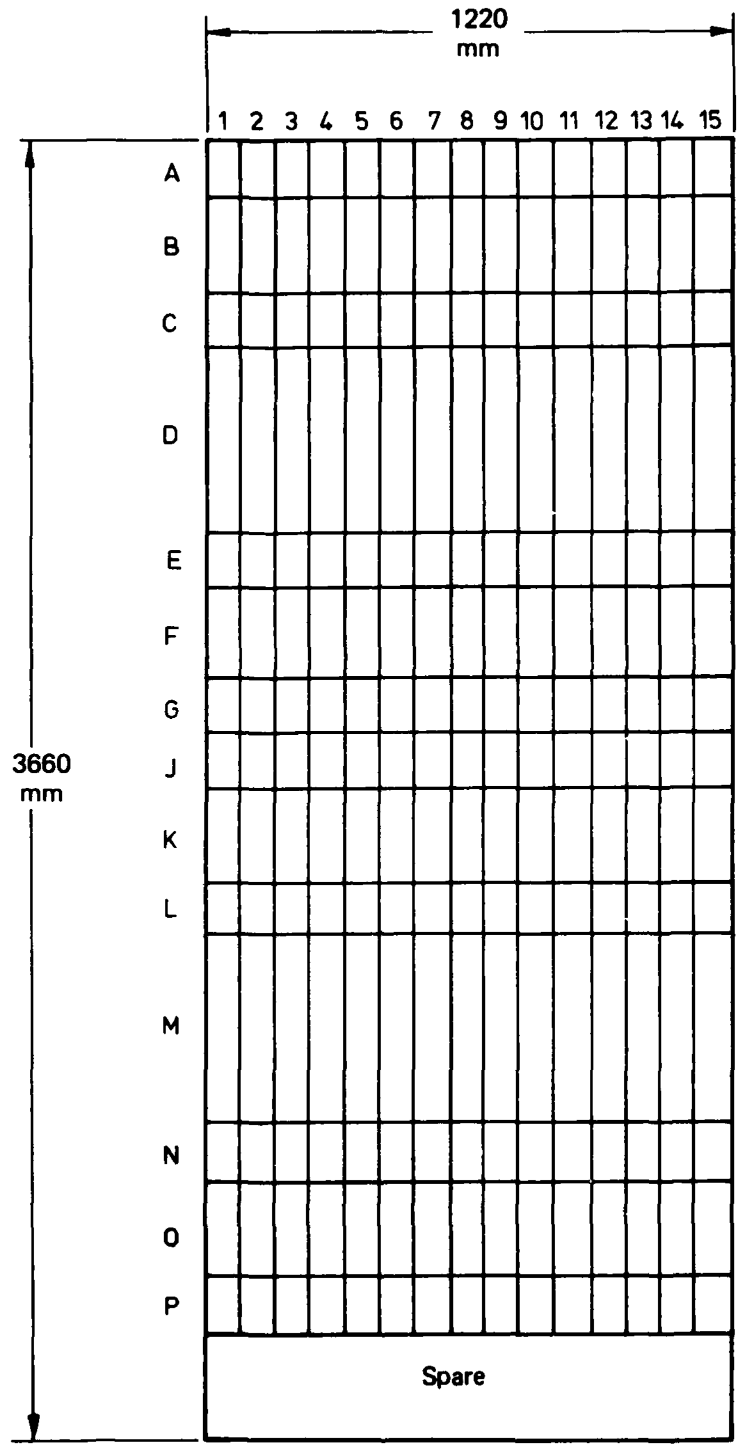


FIG. 14. 4–PIECE TIGHT BOLICONE SPECIMEN FRACTURES

(a) Specimen Al–108, S_{max} = 414 MPa
(b) Specimen Al–103, S_{max} = 207 MPa
(c) Specimen Al–106, S_{max} = 138 MPa



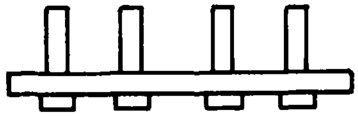
Type 1 components from sheet positions D and M

Type 2 components from sheet positions B, F, K, O

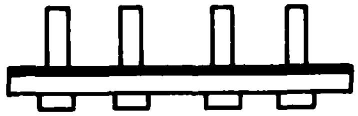
Type 3 components from sheet positions A, C, E, G, J, L, N, P

Components identified according to laboratory material code, sheet no. and position in sheet e.g. FC2A7

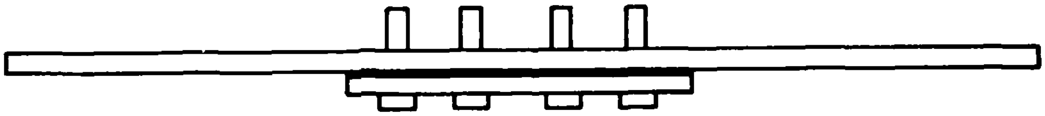
FIG. 15. COMPONENT CUTTING PLAN



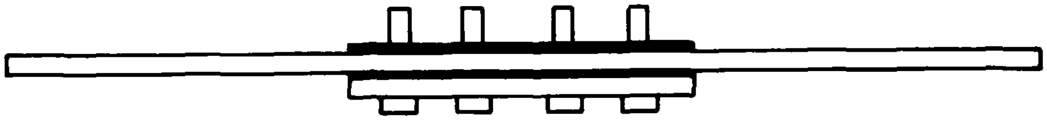
1. Eight bolts and washers assembled into one cover plate



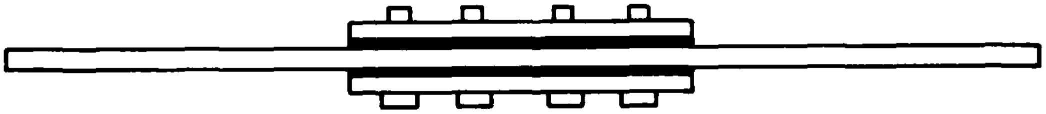
2. Corrosion–inhibitor brushed onto top surface of cover plate, taking care to avoid bolt threads



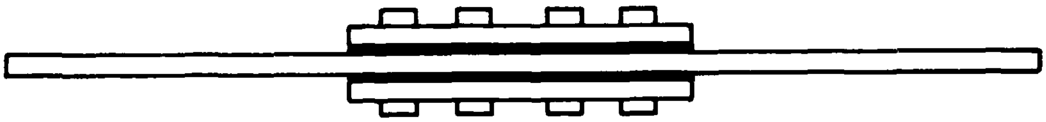
3. Centre component (s) placed on cover plate



4. Corrosion–inhibitor brushed onto top surface of centre component (s)



5. Top cover plate placed on centre component (s)



6. Washer and nuts fitted to bolts and torqued to appropriate value

FIG. 16. SPECIMEN ASSEMBLY SEQUENCE

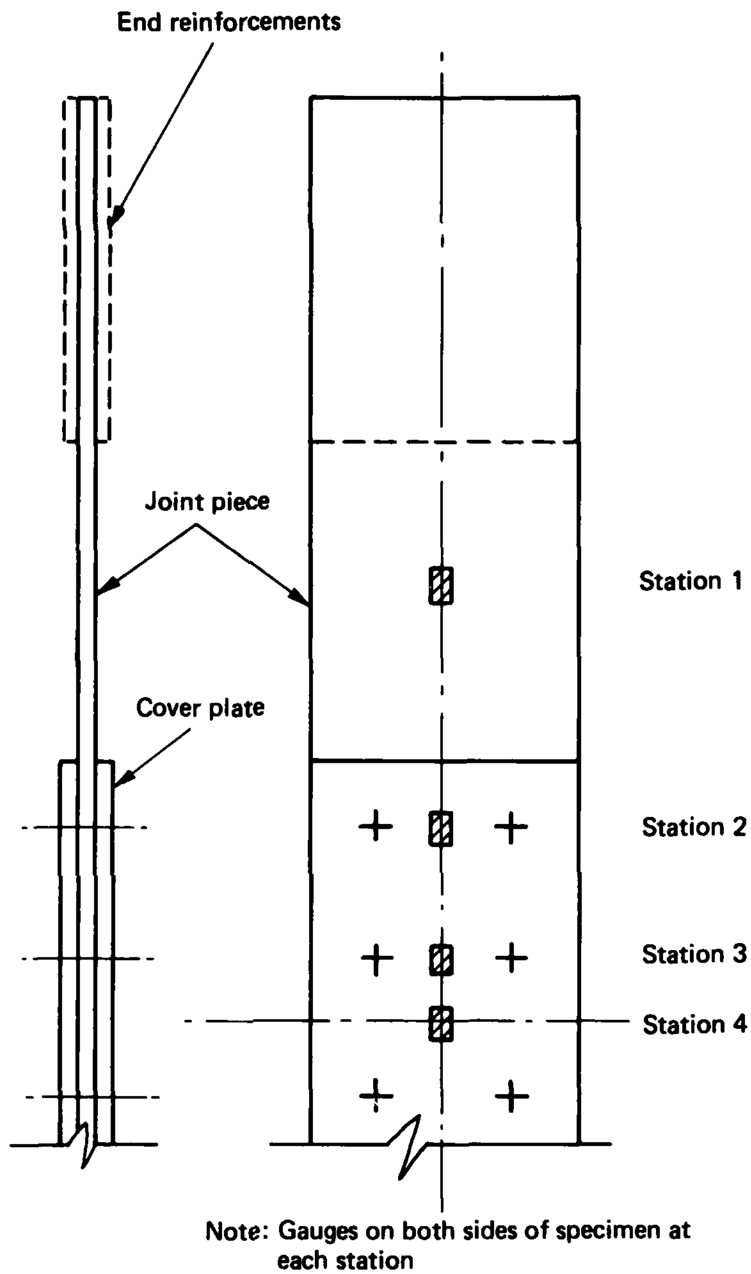


FIG. 17. POSITION OF GAUGES ON STRAIN GAUGED SPECIMENS

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16. *ABSTRACT*

Some aircraft manufacturers and operators have attempted to control in-service corrosion by the use of water-displacing organic inhibitors which can be either brushed or sprayed onto corrosion-susceptible areas of the structure. However, because of the low surface tension and lubricating properties of these preparations, concern has been expressed as to their potential side-effects on the fatigue performance of bolted and riveted joints.

Fatigue tests were carried out in repeated tension under both constant-amplitude and multi-load-level sequences on several types of 8-bolt double-lap joint specimens of 2024-T3 alcald aluminium alloy sheet. These included both low and high (100%) load transfer joints, using high and low bolt clamping forces in each case. Complementary tests were made on each type of joint assembled with either "dry" components or components coated with the corrosion inhibitor preparations LPS-3 or PX-112.

Contrary to the findings of previous investigations into the effect of inhibitors on riveted joints, the two corrosion inhibitors used were found, in general, to have either no effect or a beneficial effect on the fatigue lives of bolted joints. It is concluded that the specific effects of a water-displacing organic corrosion inhibitor on fatigue strength of joints are likely to be dependent on both the type of joint, its configuration and on the severity of the load spectrum involved.

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